

DETECTING INFRARED RADIATION

TECHNICAL FIELD OF THE INVENTION

This invention relates generally to the field of detectors and more specifically to infrared detectors.

BACKGROUND OF THE INVENTION

An infrared field may be detected using frequency upconversion whereby the infrared field is converted to a visible field. Frequency upconversion is typically  
5 achieved by generating the sum frequency of the infrared field and one or more laser drive fields through the use of second-order or third-order nonlinear optical interactions. Frequency upconversion of an infrared field may provide nearly diffraction-limited performance  
10 using a continuous wave laser source, and may have satisfactory conversion efficiency when used with a pulsed wave laser source. Conversion efficiency with a continuous wave laser source, however, may be unsatisfactory for many needs.

SUMMARY OF THE INVENTION

According to one embodiment of the present invention, detecting radiation includes receiving a first laser drive field at a cell comprising a medium having a number of states. The first laser drive field has a frequency approximately equivalent to a transition frequency between a first state and a second state of the number of states. A second laser drive field having a frequency approximately equivalent to a transition frequency between the first state and a third state of the number of states, and an infrared field having a frequency approximately equivalent to a transition frequency between the third state and a fourth state of the number of states are received. The medium has a transition between the second state and the third state substantially forbidden to support optimal coherence on the transition between the second state and the third state. The infrared field is upconverted to generate a detectable field having a frequency approximately equivalent to a transition frequency between the second state and the fourth state.

Certain embodiments of the present invention may have technical advantages. Some embodiments may benefit from some, all, or none of these advantages. A technical advantage of one embodiment may be that infrared detection occurs with high conversion efficiency with a continuous wave laser source. A phase-coherent atomic system, that is, a phaseonium, may be used to render a material system transparent to resonant laser radiation while retaining desirable nonlinear optical properties associated with the resonant response of the material system. Another technical advantage of an embodiment may be that the technique may be applicable for a broad range

of wavelengths from , for example, the near-infrared to the submillimeter spectral regions.

Other technical advantages are readily apparent to one skilled in the art from the following figures, 5 descriptions, and claims. Embodiments of the invention may include none, some, or all of the technical advantages.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention and for further features and advantages of example embodiments thereof, reference is now made to the  
5 following description, taken in conjunction with the accompanying drawings, in which:

FIGURE 1 is a block diagram illustrating one embodiment of a system for frequency upconversion;

10 FIGURE 2 is an energy diagram illustrating an example of frequency upconversion in a cell comprising an atomic vapor;

FIGURE 3 is an energy diagram illustrating an example of frequency conversion in a cell comprising atomic sodium vapor;

15 FIGURE 4 is a flowchart illustrating one embodiment of a method for frequency upconversion; and

FIGURE 5 is a band alignment diagram illustrating one example of frequency upconversion in a cell comprising a semiconductor crystal.

DETAILED DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a block diagram illustrating one embodiment of a system 50 for frequency upconversion. In general, laser drive fields 1 and 2 and an infrared field 3 propagate through a cell 5. Nonlinear wave mixing occurs among laser drive fields 1 and 2, resulting in frequency upconversion of infrared field 3 to a detectable field such as a visible field 4.

Laser drive fields 1 and 2 may operate in a spectral range including, for example, the visible and near-infrared range such as between 400 nm and 1.5 micrometers and the ultraviolet range up to 200 nm. Infrared field 3 may operate in, for example, the mid-infrared to submillimeter range from 2 to 1000 micrometers. Visible field 4 may operate in, for example, the visible to near-infrared range between 400 nm and 2 micrometers, which may be detected by highly sensitive photodetectors.

Cell 5 receives laser drive fields 1 and 2 and infrared field 3. Nonlinear mixing occurs among laser drive fields 1 and 2, resulting in a frequency upconversion of infrared field 3 to visible field 4. Cell 5 may comprise any material suitable for frequency upconversion such as an atomic or molecular vapor or semiconductor crystal. Cell 5 may comprise, for example, a vapor such as sodium vapor held in a casing comprising a substantially transparent material such as glass. Alternatively, cell 5 may comprise a semiconductor crystal held by a holder comprising a conductive material such as copper. Example embodiments of cell 5 are described in more detail with reference to FIGURES 2, 3, and 5.

A filter 6 receives laser drive fields 1 and 2 and visible field 4, and filters out laser drive fields 1 and

2. Filter 6 may comprise a filter suitable for filtering a laser drive fields 1 and 2 such as a semiconductor, dielectric plate, or grating filter. A detector such as a photodetector 7 detects visible field 4 and generates an electric signal in response to visible field 4. Photodetector 7 may comprise, for example, a photodiode for the detection of visible light. An amplifier 8 amplifies the electric signal, and a monitor displays the electric signal, which represents infrared field 3.

FIGURE 2 is an energy diagram 52 illustrating one example of frequency upconversion in one embodiment of cell 5 comprising an atomic vapor. Energy diagram 52 illustrates electronic states 10 through 13 of the atomic vapor interacting with laser drive fields 1 and 2, infrared fields 3, and visual field 4. Laser drive fields 1 and 2 are applied to the atomic medium at frequencies approximate to the resonance frequencies of the transition from state 10 to state 12 and the transition from state 10 to state 11, respectively. Infrared field 3 at a frequency approximate to the resonance frequency of the transition from state 12 to state 13 may be converted to visible field 4 at a frequency approximate to the resonance frequency of the transition from state 11 to state 13.

The values of the transition frequencies and of the corresponding frequencies of the laser drive fields 1 and 2, infrared field 3, and visible field 4 may vary, depending on the atomic vapor. In one embodiment, the frequencies may fall into the spectral ranges described with reference to FIGURE 1.

Frequency upconversion may occur with high efficiency if: (1) infrared field 3 and visible field 4 undergo negligible absorption; (2) appreciable coupling

occurs over the length of cell 5; and (3) phase matching is satisfied.

First, absorption may be negligible if the absorption lengths of infrared field 3 and visible field 4 are shorter than a characteristic coupling length, which is proportional to the amplitude of coherence between states 11 and 12. This may occur if an optimal coherence is supported in a medium such as a phaseonium medium, which may be realized if: (1) the intensities of laser drive fields 1 and 2 are of the order of saturation intensities of their corresponding transitions, which may be between 0.1 and 10 kW/cm<sup>2</sup> for the typical optical transitions of atoms; and (2) the laser drive fields 1 and 2 are sufficiently detuned from resonance frequencies of the medium, where the detuning intensities of laser drive fields 1 and 2 is substantially equivalent to at least the total linewidths of the corresponding transitions.

Second, for appreciable coupling to occur over the length of cell 5, the detuning of laser drive fields 1 and 2 may be restricted to be not much greater than the above linewidths. The detuning of laser drive fields 1 and 2 may be approximately equal to the total linewidths of the transition from state 10 to state 11 and the transition from state 10 to state 12, respectively. For atomic vapors, the detuning may be from 0.1 to 10 GHz.

Third, the phase matching condition may be satisfied when the nonlinear susceptibility of the atomic medium at frequencies of infrared field 3 and visible field 4 is approximately equal to the linear susceptibility, which may be achieved under the conditions specified above. Phase matching may be improved by allowing for a small

angle, for example, less than 1 degree, between the propagation directions of laser drive fields 1 and 2.

FIGURE 3 is an energy diagram 54 illustrating an example of frequency upconversion in one embodiment of cell 5 comprising atomic sodium vapor. Electronic states 10, 11, 12, and 13 correspond to sodium levels 3s, 3p, 11p, and 12s, respectively. Laser drive fields 1 and 2 may be applied at wavelengths of approximately 248 nm and 589 nm, respectively. Infrared field 3 at a wavelength of approximately 100 micrometers may be converted to visible field 4 of a wavelength of approximately 425 nm.

In one embodiment, cell 5 may comprise a vapor with a sodium number density approximately equal to  $10^{16} \text{ cm}^{-3}$ . A substantially transparent casing such as a glass casing with, for example, a length of approximately 0.5 to 10 cm and a diameter of approximately 0.2 to 1 cm may be used to hold the vapor. The detuning of laser drive fields 1 and 2 may be approximately equal to 1 GHz. The intensity of laser drive field 1 may be greater than  $500 \text{ W/cm}^2$ , and the intensity of laser drive field 2 may be greater than  $13 \text{ mW/cm}^2$ . In the embodiment, infrared field 3 may be efficiently converted to visible field 4.

FIGURE 4 is a flowchart illustrating one embodiment of a method for frequency upconversion. The method starts at step 14, where laser drive fields 1 and 2 illuminate cell 5. Laser drive fields 1 and 2 create a coherence between electronic states 11 and 12 at step 15. At step 16, an infrared field 3 incident on cell 5 is converted to visible field 4.

At step 17, filter 6 receives laser drive fields 1 and 2 and visible field 4 and filters out laser drive fields 1 and 2, allowing visible field 4 to propagate through filter 6. Visible field 4 is detected by

photodetector 7 at step 18, which generates a signal. The signal from photodetector 7 is amplified by amplifier 8 at step 19. The signal from amplifier 8 is displayed on monitor 9 at step 20.

5       FIGURE 5 is a band alignment diagram 56 illustrating one example of frequency upconversion in one embodiment of cell 5 that has a number of levels. Cell 5 may comprise a semiconductor crystal held by a holder comprising a conductive material such as copper and that  
10 acts as a heat sink. The semiconductor crystal may be several hundred micrometers in size. Cell 5 may be placed in a cryostat with liquid nitrogen of approximately 77° Kelvin.

Cell 5 may comprise, for example, a number of  
15 quantum wells or quantum dots. Band alignment diagram 56 describes a quantum dot 21. Quantum dot 21 may comprise, for example, a three-dimensional island of InAs of a suitable size such as approximately 5 to 20 nm deposited on GaAs. Quantum dot 21 may be grown using standard  
20 molecular-beam epitaxy on a GaAs substrate in a Stranski-Krastanov growth mode. The edge of a valence band 22 and the edge of a conduction band 23 may form a three-dimensional potential well for holes and electrons, respectively, and the hole and electron levels may become  
25 quantized. Band alignment diagram 56 also shows a hole level 24 and electron levels 25 and 26. In an alternative embodiment, level 24 may be an electron level, and levels 25 and 26 may be hole levels.

The transitions allowed by selection rules may occur  
30 if hole level 24 and electron levels 25 and 26 have the same principal quantum number  $n = 1$ , but hole level 24 and electron levels 25 and 26 may have different orbital quantum numbers. Laser drive field 27 is applied to a

system of quantum dots at a photon energy approximate to the transition energy between electron levels 24 and 25, for example, between 1 and 1.3 eV. Strong absorption may be avoided if the photon energy of laser drive field 27  
5 is less than the resonance energy of the transition from hole level 24 to electron level 25 by approximately 10 to 20 meV.

Infrared field 3 at a frequency approximate to the transition frequency between electron levels 25 and 26  
10 may be converted to visible field 4 at a frequency approximate to the transition frequency between hole level 24 and electron level 26. Efficient upconversion may be achieved using a stack of 10 to 20 layers of InAs quantum dots 21 with a sheet density approximately equal  
15 to  $10^{11} \text{ cm}^{-2}$ .

Certain embodiments of the present invention may have technical advantages, although all embodiments may not necessarily benefit from these advantages. A technical advantage of one embodiment may be that  
20 infrared detection occurs with high conversion efficiency with a continuous wave laser source. A phase-coherent atomic system, that is, a phaseonium, may be used to render a material system transparent to resonant laser radiation while retaining desirable nonlinear optical  
25 properties associated with the resonant response of the material system. Another technical advantage of an embodiment may be that the technique may be applicable for a broad range of wavelengths from the near-infrared to the submillimeter spectral regions, for example, from  
30 0.7 to 1000 micrometers.

Although embodiments of the invention and their advantages are described in detail, a person skilled in the art could make various alterations, additions, and

omissions without departing from the spirit and scope of  
the present invention as defined by the appended claims.